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The Galactic and Sub-Galactic Environments of Short-Duration Gamma-Ray Bursts: Implications for the Progenitors

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Abstract

The study of short-duration gamma-ray bursts (GRBs) has undergone a revolution in recent years thanks to the discovery of the first afterglows and host galaxies in May 2005. In this review we summarize our current knowledge of the galactic and sub-galactic environments of short GRBs, and the implications for the progenitor population. The most crucial results are: (i) some short GRBs occur in elliptical galaxies; (ii) the majority of short GRBs occur in star forming galaxies; (iii) the star forming hosts of short GRBs are distinct from the host galaxies of long GRBs in terms of star formation rates, luminosities, and metallicities, and instead appear to be drawn from the general field galaxy population; (iv) the physical offsets of short GRBs relative to their host galaxy centers are significantly larger than for long GRBs; (v) the observed offset distribution agrees well with predictions for the locations of NS-NS binary mergers; and (vi) unlike long GRBs, which tend to occur in the brightest regions of their hosts, the environments of short GRBs generally under-represent the light distribution of their host galaxies. Taken together, these observations suggest that short GRB progenitors have a wide age distribution and generally track stellar mass rather than star formation activity. These results are fully consistent with NS-NS binary mergers, but partial contribution from prompt or delayed magnetar formation is also consistent with the data.

1 Introduction

One of the most fundamental questions in the study of astrophysical transient phenomena is the identity of their underlying progenitor systems. The connection between transients and progenitors provides insight into the energy source and the explosion/eruption mechanism, events rates and their evolution over cosmic time, and a census of the birth and destruction rates of compact objects (white dwarfs, neutron stars, and black holes). Ideally, a unique association between transient events and their progenitors may come from the identification of individual progenitor systems in pre-explosion observations. For example, the progenitor of supernova SN 1987A in the Large Magellanic Cloud was a blue supergiant (e.g., Gilmozzi et al. 1987), while the progenitors of several type IIP supernovae (SNe) have been identified as red supergiants (e.g., Smartt 2009). Unfortunately, for a wide range of cosmic explosions, the low rate of nearby events

and/or the intrinsic faintness of the likely progenitor systems preclude a direct identification at the present.

In such cases we may still gain deep insight into the nature of the progenitors through statistical studies of the galactic and local environments of the explosions. For example, past studies of supernova environments have demonstrated that Type Ia and Type Ib/Ic/II events arise from distinct progenitor systems since the former are located in a wide range of galaxy types, while the latter occur only in star forming galaxies, pointing to a direct link with massive stars (e.g., van den Bergh et al. 2005). In a similar vein, long-duration gamma-ray bursts (GRBs) were initially linked with massive stars through their exclusive association with star forming galaxies (e.g., Bloom et al. 1998; Djorgovski et al. 1998; Fruchter et al. 1999). This connection was subsequently confirmed by the presence of accompanying type Ic core-collapse SNe (e.g., Hjorth et al. 2003; Stanek et al. 2003).

In this review we focus on the study of the galactic and sub-galactic environments of short-duration GRBs (T90 $\lesssim$ 2 s), and discuss the implications for their still unknown progenitors. This study is in its nascent stages. Short GRB afterglows were only discovered in 2005 and the discovery rate of new events is modest ($\sim$ 10 per year). Still, the sample is now large enough that we can begin to examine the environments of short GRBs, particularly in comparison with long GRB hosts and field galaxy samples, as well as with theoretical expectations for popular progenitor models such as NS-NS and NS-BH binary mergers (Eichler et al. 1989; Narayan et al. 1992). In §2 we discuss the identification of short GRB host galaxies and measurements of their redshifts. The galactic-scale properties (luminosities, star formation rates, and metallicities) are described in §3. Finally, in §4 we focus on the locations of short GRBs within their host galaxies, partly in comparison to long GRBs and NS-NS merger predictions. The basic results of these studies are that the progenitors of short GRBs are distinct from the massive star progenitors of long GRBs, that they are related to an older stellar population, and that short GRB progenitors reside in average environments within a representative sample of galaxies, likely selected by mass rather than by star formation.

The material presented in this review draws heavily from three recent papers on the properties of short GRBs and their host galaxies — Berger et al. (2007b), Berger (2009), and Fong et al. (2009) — and we refer the reader to these papers for additional details.

2 Host Galaxy Identifications and Redshifts

The discovery of afterglow emission from short GRBs starting in May 2005 led to the first identifications of their host galaxies and hence to redshift measurements. The first short burst to be localized to a positional accuracy of a few arcseconds, GRB 050509b, appeared to coincide with the outskirts of an elliptical galaxy at $z = 0.226$ (Gehrels et al. 2005; Hjorth et al. 2005a; Bloom et al. 2006). However, the statistical significance of the association was only $\sim 10^{-3}$, and the afterglow error circle contained several fainter galaxies possibly at higher redshift. Only two months later, the afterglow of GRB 050709 was localized to a sub-arcsecond position coincident with the outskirts of an irregular star forming galaxy at $z = 0.161$ (Fox et al. 2005). Despite the on-going star formation activity within the host galaxy, the burst was not accompanied by a supernova explosion, indicating that the progenitor was not likely to be a massive star (Hjorth et al. 2005b). However, due to the presence of active star formation an association with a young progenitor system such as a magnetar could not be excluded.

The discovery of X-ray, optical, and radio afterglow emission from GRB 050724 finally estab-

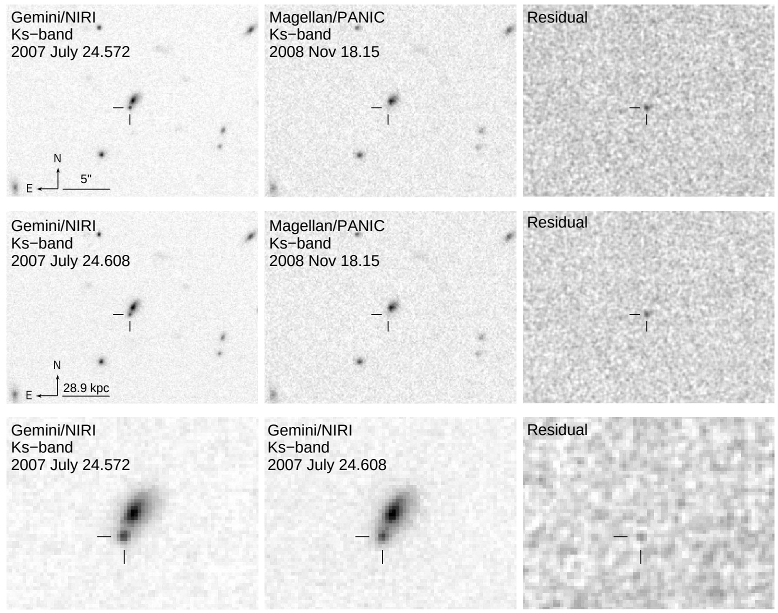

Figure 1: Discovery of the near-infrared afterglow of GRB 070724. In each row we display the afterglow image, template image, and residual image. The afterglow coincides with the disk of an edge-on galaxy. From Berger et al. (2009).

lished a direct link with an old stellar population (Berger et al. 2005). The burst was localized to an elliptical galaxy at $z = 0.257$ with no evidence for on-going star formation ($\lesssim 0.05$ M$_\odot$ yr^{-1}) and a stellar population age of $\gtrsim 1$ Gyr. The absence of star formation activity and an associated supernova demonstrated a connection with an old stellar population.

The combination of low redshifts ($z \sim 0.1 - 0.3$) and apparent dominance of early-type host galaxies in the early sample of short GRBs led to initial claims of a particularly old progenitor population: $\tau \gtrsim 4$ Gyr (Nakar et al. 2006), $\tau \gtrsim 7$ Gyr (Zheng & Ramirez-Ruiz 2007), $\tau \sim$ several Gyr (Gal-Yam et al. 2008). Indeed, some authors have noted a possible inconsistency with the delay time distribution of NS-NS binaries (Nakar et al. 2006), although population synthesis models of NS-NS binary formation and mergers have led to opposite claims (Belczynski et al. 2006). Clearly, the sample of short GRBs with afterglow detections that was available when these various claims were published was very small (4 events: GRBs 050509b, 050709, 050724, and 051221).

Fortunately, the continued detection of short GRBs, primarily by *Swift*, and a community-wide concerted effort to detect and study their afterglows led to a substantial increase in the sample (e.g., Figures 1 and 2), and a re-evaluation of the host galaxy demographics and redshift distribution. For comprehensive summaries of the host galaxy properties we refer the reader to Berger et al. (2007b) and Berger (2009). The first comprehensive study of this sample, and the implications for the redshift distribution of short GRBs, was presented in Berger et al. (2007b). Using optical follow-up observations of nine short GRBs with afterglows available as of the end of 2006 we found that eight are likely associated with faint galaxies, $R \sim 23 - 26.5$ mag. By comparison to the early host galaxies (with $R \sim 17 - 22$ mag and $z \lesssim 0.5$), as well as the hosts of long GRBs and large field galaxy samples, we demonstrated that these new host galaxies likely reside at $z \sim 1$; see Figure 3. Indeed, spectroscopic redshifts for the four *brightest* hosts led to $z \approx 0.4 - 1.1$. The current redshift distribution of short GRBs (in comparison to long GRBs) is

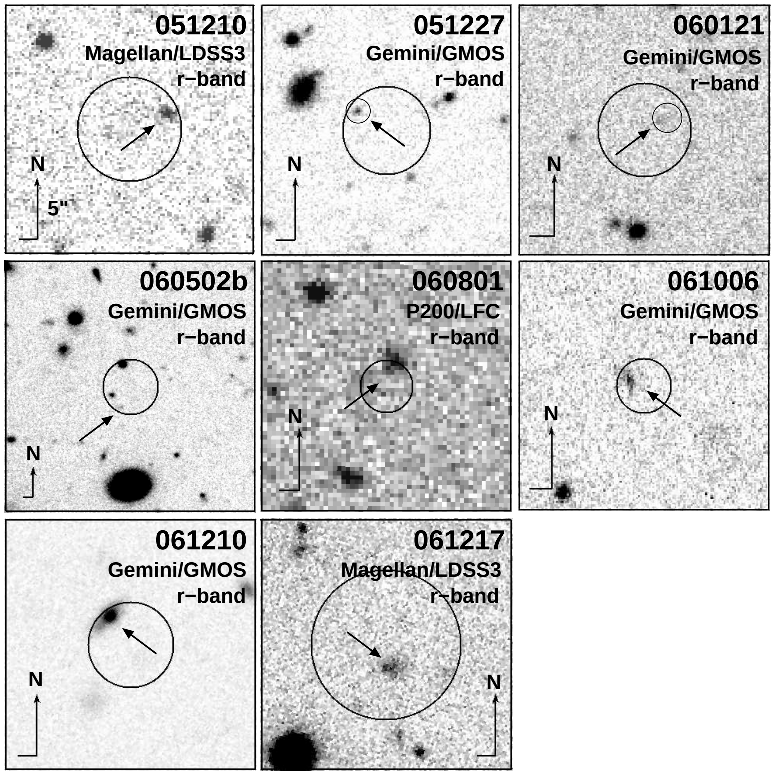

Figure 2: Ground-based images from Magellan and Gemini of several short GRB hosts. All images are $20''$ on a side, with the exception of GRB 060502b which is twice as large. The large circles mark the XRT error regions, while smaller circles mark the positions of the optical afterglows (when available). Arrows mark the positions of the hosts. From Berger et al. (2007b).

shown in Figure 4.

These observations established for the first time that $1/3 - 2/3$ of all short GRBs originate at $z \gtrsim 0.7$, and that some bursts produce $10^{50} - 10^{52}$ erg in their prompt emission, at least two orders of magnitude larger than the low redshift short bursts. Most importantly, with this new high redshift sample, we found tighter constraints on the progenitor age distribution than previously possible. Viable models include a wide log-normal distribution with $\tau_* \sim 4 - 8$ Gyr, or a power law distribution, $P(\tau) \propto \tau^n$, with $-1 \lesssim n \lesssim 0$ (Berger et al. 2007b).

3 Host Galaxy Luminosities, Metallicities, and Star Formation Rates

The association of some short GRBs with elliptical galaxies demonstrated unambiguously that at least some of the progenitors are related to an old stellar population. However, as we discussed in the previous section, a substantial fraction of short GRBs ($1/3-2/3$) reside at higher redshifts than previously suspected, $z \sim 1$ (Berger et al. 2007b), and spectroscopic observations indicate that most of these galaxies are undergoing active star formation. Indeed, in the sample of short GRBs localized to better than a few arcseconds about 50% reside in star forming galaxies compared to only $\approx 10\%$ in elliptical galaxies; the remaining $\approx 40\%$ are currently unclassified due to their faintness, a lack of obvious spectroscopic features, or the absence of sensitive follow-

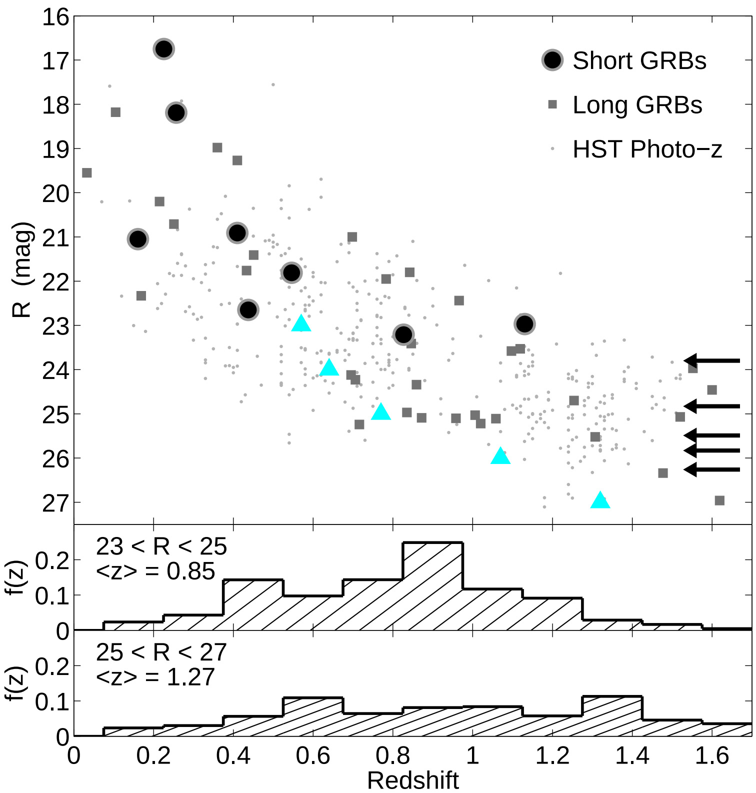

Figure 3: Host galaxy R magnitudes as a function of redshift for short GRBs (solid black circles, arrows), long GRBs (gray squares), and galaxies in the HST/ACS Early Release Observation fields VV 29 (UGC 10214) and NGC 4676 (Benítez et al. 2004). The upward pointing triangles indicate the median redshift of a galaxy sample complete to the appropriate magnitude limit (Coe et al. 2006). For $R \gtrsim 26$ mag appropriate for our sample the median redshift is about 1.1. The bottom panels show the redshift distributions of galaxies in two magnitude bins from spectroscopic ($23 < R < 25$ mag; Cowie et al. 2004; Wirth et al. 2004) and photometric ($25 < R < 27$ mag; Coe et al. 2006) redshift surveys. The clear magnitude-redshift relation for short GRB hosts suggests that the faint host galaxies are located at $z \sim 1$. From Berger et al. (2007b).

up observations. This result raises the question of whether some short GRBs are related to star formation activity rather than an old stellar population, and if so, whether the star formation properties are similar to those in long GRB host galaxies. The answer will shed light on the diversity of short GRB progenitors.

As of December 2007, the sample of host galaxies with spectroscopic observations was comprised of 6 systems with sub-arcsecond afterglow positions, and an equal number based on only *Swift*/XRT positions ($2-5$ arcsec). The distribution of absolute rest-frame B-band magnitudes (M_B) for these 12 host galaxies ranges from about 0.1 to 1.5 L_* (Berger 2009), with the exception of the possible elliptical host galaxy of GRB 050509b with $L_B \approx 5$ L_* (Bloom et al. 2006).

The star formation rates inferred from the [OII]λ3727 line using the standard conversion (Kennicutt 1998), indicate values of $0.2-6$ M$_\odot$ yr^{-1}, while the elliptical hosts have upper limits of $\lesssim 0.1$ M$_\odot$ yr^{-1}. Combined with the absolute magnitudes, we find specific star formation rates of SFR/$L_B \approx 1-10$ M$_\odot$ yr^{-1} L_*^{-1} for the star forming hosts (and $\lesssim 0.03$ M$_\odot$ yr^{-1} L_*^{-1} for the elliptical hosts). The SSFR values as a function of redshift are shown in Figure 5.

Finally, for five of the twelve host galaxies we have sufficient spectral information to

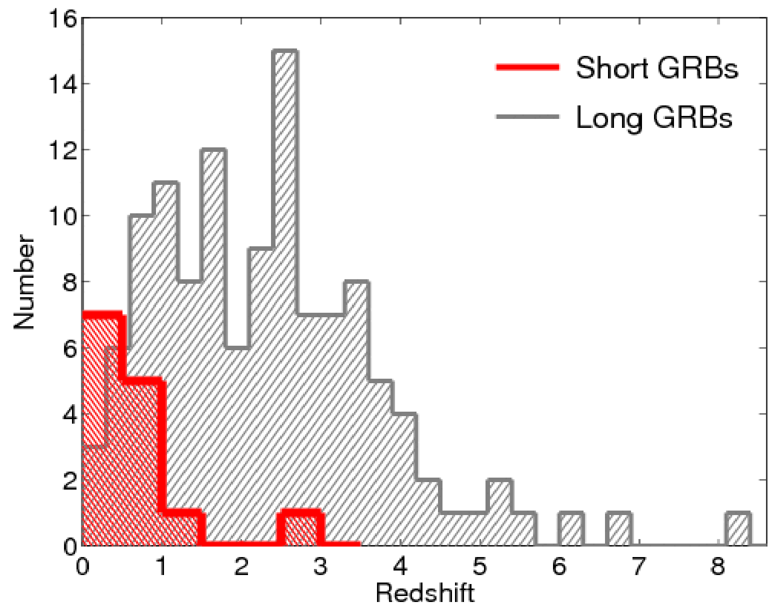

Figure 4: The redshift distribution of long and short GRBs as of late 2009.

measure the metallicity. We use the standard metallicity diagnostics, $R_{23} \equiv (F_{[\mathrm{OII}]\lambda3727} + F_{[\mathrm{OIII}]\lambda\lambda4959,5007})/F_{\mathrm{H}\beta}$ (Pagel et al. 1979; Kobulnicky & Kewley 2004) and $F_{[\mathrm{NII}]\lambda6584}/F_{\mathrm{H}\alpha}$. The value of R_{23} depends on both the metallicity and ionization state of the gas, which we determine using the ratio of oxygen lines, $O_{32} \equiv F_{[\mathrm{OIII}]\lambda\lambda4959,5007}/F_{[\mathrm{OII}]\lambda3727}$. We note that the R_{23} diagnostic is double-valued with low and high metallicity branches (e.g., Kewley & Dopita 2002). This degeneracy can be broken using [NII]/Hα when these lines are accessible. To facilitate a subsequent comparison with field galaxies we use the R_{23}, O_{32}, and [NII]/Hα calibrations of Kobulnicky & Kewley (2004). The typical uncertainty inherent in the calibrations is about 0.1 dex.

Adopting the solar metallicity from Asplund et al. (2005), $12 + \log(\mathrm{O/H}) = 8.66$ we find $12 + \log(\mathrm{O/H}) \approx 8.6$ for the upper R_{23} branch and $\approx 8.0 - 8.5$ for the lower branch for the host of GRB 061006. For the host of GRB 070724 we find $12 + \log(\mathrm{O/H}) \approx 8.9$ for the upper branch, and $\approx 7.6{-}8.1$ for the lower branch. We find a similar range of values for the host of GRB 061210, but the ratio $F_{[\mathrm{NII}]}/F_{\mathrm{H}\alpha} \approx 0.2$, indicates $12 + \log(\mathrm{O/H}) \gtrsim 8.6$, thereby breaking the degeneracy and leading to the upper branch solution, $12 + \log(\mathrm{O/H}) \approx 8.9$. For the host of GRB 051221a we use the line fluxes provided in Soderberg et al. (2006), and derive similar values to those for the host of GRB 070724. Finally, for the host galaxy of GRB 050709 we lack a measurement of the [OII] emission line, and we thus rely on [NII]/Hα to infer $12 + \log(\mathrm{O/H}) \approx 8.5$. The dominant source of uncertainty in this measurement is the unknown value of O_{32}, but using a spread of a full order of magnitude results in a metallicity uncertainty of 0.2 dex. For the hosts with double-valued metallicities (GRBs 051221a, 061006, and 070724) we follow the conclusion for field galaxies of similar luminosities and redshifts that the appropriate values are those for the R_{23} upper branch (Kobulnicky & Kewley 2004). This conclusions was advocated by Kobulnicky & Kewley (2004) based on galaxies in their sample with measurements of both R_{23} and [NII]/Hα. It is similarly supported by our inference for the host galaxy of GRB 061210. The metallicities as a function of host luminosity are shown in Figure 6.

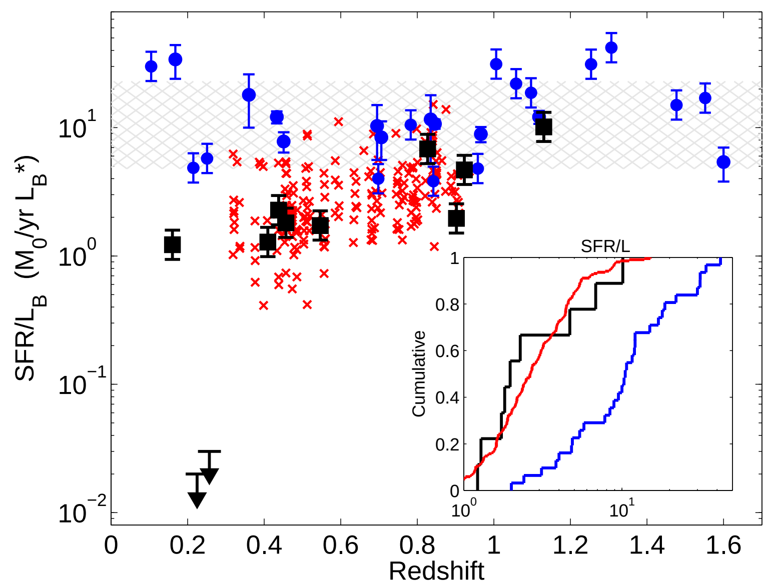

Figure 5: Specific star formation rates as a function of redshift for the host galaxies of short GRBs (black squares), long GRBs (blue circles) and field galaxies from the GOODS-N survey (red crosses; Kobulnicky & Kewley 2004). Upper limits for the elliptical hosts of GRBs 050509b and 050724 are also shown. The cross-hatched region marks the median and standard deviation for the long GRB host sample. The inset shows the cumulative distributions for the three samples. The K-S probability that the short and long GRB hosts are drawn from the same distribution is only 0.3%, while the strong overlap with the field sample leads to a K-S probability of 60%. From Berger (2009).

To place the host galaxies of short GRBs in a broader context we compare their properties with those of long GRB hosts and field star forming galaxies from the GOODS-N survey (Kobulnicky & Kewley 2004). In terms of absolute magnitudes, the long GRB hosts range from $M_B \approx -15.9$ to -21.9 mag, with a median value of $\langle M_B \rangle \approx -19.2$ mag ($\langle L_B \rangle \approx 0.2\ L_*$; Berger et al. 2007a). Thus, the long GRB hosts extend to lower luminosities than the short GRB hosts, with a median value that is about 1.1 mag fainter. A Kolmogorov-Smirnov (K-S) test indicates that the probability that the short and long GRB hosts are drawn from the same underlying distribution is 0.1. On the other hand, a comparison to the GOODS-N sample reveals a similar distribution, and the K-S probability that the short GRB hosts are drawn from the field sample is 0.6.

We reach a similar conclusion based on a comparison of specific star formation rates. For long GRB hosts the inferred star formation rates range from about 0.2 to 50 $M_\odot$ yr^{-1}, and their specific star formation rates are about $3-40$ $M_\odot$ yr^{-1} L_*^{-1}, with a median value of about 10 $M_\odot$ yr^{-1} L_*^{-1} (Christensen et al. 2004). As shown in Figure 5, the specific star formation rates of short GRB hosts are systematically lower than those of long GRB hosts, with a median value that is nearly an order of magnitude lower. Indeed, the K-S probability that the short and long GRB hosts are drawn from the same underlying distribution is only 3.5×10^{-3}. This is clearly seen from the cumulative distributions of specific star formation rates for each sample (inset of Figure 5). On the other hand, a comparison to the specific star formation rates of the GOODS-N field galaxies reveals excellent agreement (Figure 5). The K-S probability that the short GRB hosts are drawn from the field galaxy distribution is 0.6. Thus, short GRB hosts are drawn from the normal population of star forming galaxies at $z \lesssim 1$, in contrast to long GRB

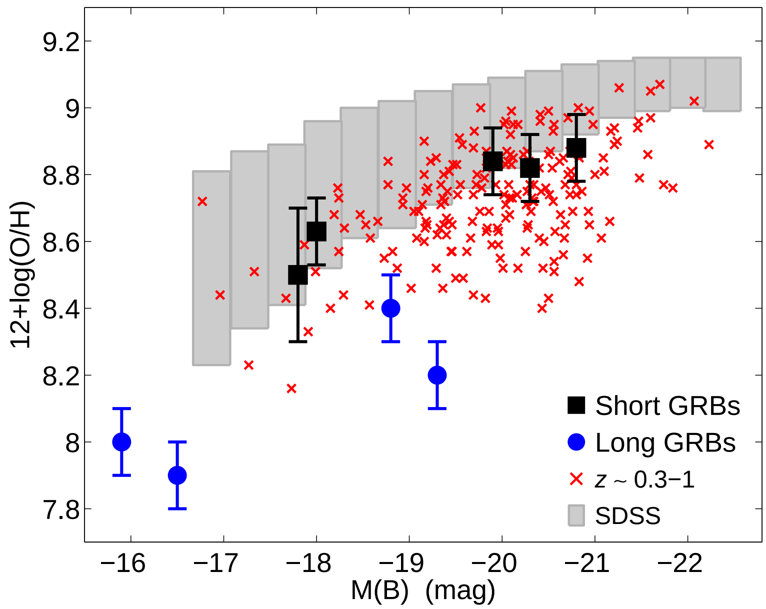

Figure 6: Metallicity as a function of B-band absolute magnitude for the host galaxies of short GRBs (black squares) and long GRBs (blue circles). The gray bars mark the $14-86$ percentile range for galaxies at $z \sim 0.1$ from the Sloan Digital Sky Survey (Tremonti et al. 2004), while red crosses designate the same field galaxies at $z \sim 0.3-1$ shown in Figure 5 (Kobulnicky & Kewley 2004). Both field samples exhibit a clear luminosity-metallicity relation. The long GRB hosts tend to exhibit lower than expected metallicities (Stanek et al. 2006), while the hosts of short GRBs have higher metallicities by about 0.6 dex, are moreover in excellent agreement with the luminosity-metallicity relation. From Berger (2009).

hosts, which have elevated specific star formation rates, likely as a result of preferentially young starburst populations (Christensen et al. 2004; Savaglio et al. 2008).

Finally, the metallicities measured for short GRB hosts are in excellent agreement with the luminosity-metallicity relation for field galaxies at $z \sim 0.1-1$ (Figure 6; Kobulnicky & Kewley 2004; Tremonti et al. 2004). The two hosts with $M_B \approx -18$ mag have $12 + \log(\mathrm{O/H}) \approx 8.6$, while those with $M_B \approx -20$ to -21 mag have $12 + \log(\mathrm{O/H}) \approx 8.8 - 8.9$, following the general trend. On the other hand, the short GRB host metallicities are systematically higher than those of long GRB hosts, which have been argued to have lower than expected metallicities (Stanek et al. 2006). The median metallicity of short GRB hosts is about 0.6 dex higher than for long GRB hosts, and there is essentially no overlap between the two host populations.

To conclude, the short GRB host sample is dominated by star forming galaxies, but these galaxies have higher luminosities, lower star formation rates and specific star formation rates, and higher metallicities than the star forming host galaxies of long GRBs. Instead, the short GRB host sample appears to be drawn from the typical field galaxy population represented for example by the GOODS survey. These results suggest that while short GRB hosts are mainly star forming galaxies, the progenitor population most likely traces stellar mass rather than star formation activity.

4 *Hubble Space Telescope* Study of the Galactic and Sub-galactic Environments of Short GRBs

High angular resolution imaging of short GRB host galaxies can provide detailed information on the host morphologies and for the first time, the burst sub-galactic environments. In Fong et al. (2009) we performed the first comprehensive analysis of *HST* observations of short GRB host galaxies. We used a sample of 10 events covering the period of May 2005 to December 2006. Of these 10 bursts, seven have been localized to sub-arcsecond precision and of those, six are robustly associated with host galaxies (for details see Fong et al. 2009). In two cases the identity of the host remains unclear. Illustrative examples of the host images and morphological model fits are shown in Figure 7. To study the sub-galactic environments we used the offsets relative to the host center and the fractional flux at the GRB position.

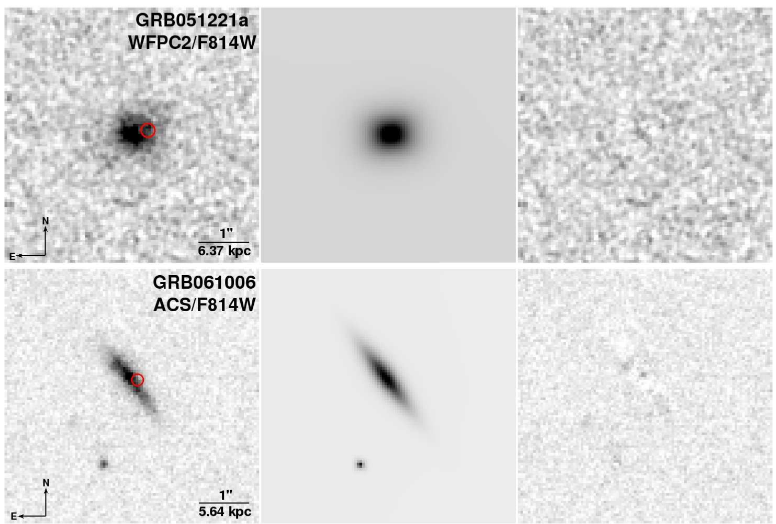

Figure 7: Top: *HST*/WFPC2/F814W image of the host galaxy of GRB 051221 with a 5σ error circle representing the afterglow position. *Center:* Sérsic model fit from `galfit`. *Right:* Residual image. Bottom: Same, but for the host galaxy of GRB 061006. From Fong et al. (2009).

4.1 Morphological Analysis

We modeled the two-dimensional surface brightness distributions of the host galaxies to determine their effective radii and morphological properties such as the Sérsic n index. We found that three hosts (GRBs 050709, 051221a, and 061006) are best modeled with $n \approx 1$, corresponding to an exponential disk profile, while two hosts (GRBs 050509b and 050724) are best modeled with $n \approx 3$ and ≈ 5.6, respectively, typical of elliptical galaxies. The final three hosts (GRBs 051210, 060121, and 060313) are equally well modeled with a wide range of n values, although $n \sim 1$ is preferred. Therefore, of the eight short GRB host galaxies with *HST* observations only two can be robustly classified as elliptical galaxies based on their morphology. A similar fraction was determined independently from spectroscopic observations (§3; Berger 2009).

The morphological analysis also yields values of the galaxy effective radii, r_e. We find a range of $\approx 0.2 - 5.8''$, corresponding to physical scales[1] of about $1.4 - 21$ kpc. The smallest

[1]For the faint hosts without a known redshift (GRBs 051210, 060121, 060313, and possibly 061201) we assume

effective radius is measured for the host of GRB 060313, while the host of GRB 050509b has the largest effective radius. The median value is $r_e \approx 3.5$ kpc. The effective radii as a function of n are shown in Figure 8. Also shown are the same r_e and n values for the hosts of long GRBs from Wainwright et al. (2007).

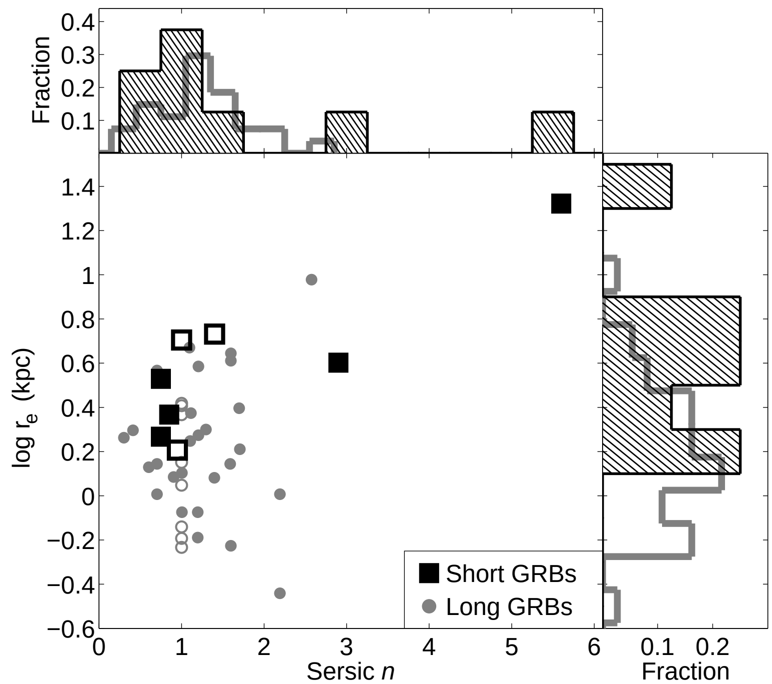

Figure 8: Effective radii for the short GRB hosts with *HST* observations plotted as a function of their Sérsic n values. Also shown are the data for long GRB hosts based on *HST* observations (Wainwright et al. 2007). The hosts of GRBs 050509b and 050724 have n values typical of elliptical galaxies, but the remaining hosts have a similar distribution to that of long GRBs (i.e., a median of $n \sim 1$, or an exponential disk profile). On the other hand, the hosts of short GRBs are larger by about a factor of 2 than the hosts of short GRBs, in agreement with their higher luminosities. From Fong et al. (2009).

Two clear trends emerge from this comparison. First, all long GRB hosts have $n \lesssim 2.5$, and the median value for the population is $\langle n \rangle \approx 1.1$ (Wainwright et al. 2007). Thus, all long GRB hosts are morphologically classified as exponential disks, while 2 of the 8 short GRB hosts studied here exhibit de Vaucouleurs elliptical galaxy profiles. However, for the hosts with $n \lesssim 2$, the distributions of n values for both populations appear to be similar.

Second, short GRB hosts have larger effective radii, with $\langle r_e \rangle \approx 3.5$ kpc, compared to $\langle r_e \rangle \approx 1.7$ kpc for long GRB hosts (Wainwright et al. 2007). A K-S test indicates that the probability that the short and long GRB hosts are drawn from the same underlying distribution of host galaxy effective radii is only 0.04. Thus, we conclude with high significance that short GRB host galaxies are systematically larger than long GRB hosts. The larger sizes of short GRB hosts are expected in the context of the galaxy size-luminosity relation (e.g., Freeman 1970) and the higher luminosity of short GRB hosts (§3; Berger 2009).

An additional striking difference between the hosts of long and short GRBs is the apparent dearth of interacting or irregular galaxies in the short GRB sample. Of the eight short

$z = 1$ (Berger et al. 2007b), and take advantage of the relative flatness of the angular diameter distance as a function of redshift beyond $z \sim 0.5$.

GRB host galaxies only one exhibits an irregular morphology (GRB 050709) and none appear to be undergoing mergers. In contrast, the fraction of long GRB hosts with an irregular or merger/interaction morphology is about $30-60\%$ (Wainwright et al. 2007). The interpretation for this high merger/interaction fraction in the long GRB sample is that such galaxies are likely undergoing intense star formation activity triggered by the merger/interaction process, and are therefore suitable sites for the production of massive stars. The lack of morphological merger signatures in the short GRB sample indicates that if any of the hosts have undergone significant mergers in the past, the delay time between the merger and the production of a short GRB is $\gtrsim 10^9$ yr (e.g., Barnes & Hernquist 1992).

4.2 Offset Distribution

Based on the astrometric tie of the *HST* host observations to ground-based afterglow observations, we found that the projected offsets of the bursts relative to their host galaxy centers are in the range of $\approx 0.12-17.7''$. The corresponding projected physical offsets are about $1-64$ kpc, with a median value of about 3 kpc. The largest offsets are measured for GRBs 050509b and 051210, but these are based on *Swift*/XRT positions only, with statistical uncertainties of about 12 and 18 kpc, respectively. If we consider only the bursts with sub-arcsecond afterglow positions we find that the largest offset is 3.7 kpc (GRB 050709), and that the median offset for the 6 bursts is 2.2 kpc. In the case of GRB 061201 the host association remains ambiguous, but even for the nearest detected galaxy the offset is about 14.2 kpc.

To investigate the offset distribution in greater detail we supplement the values measured from the *HST* observations with offsets for GRBs 070724, 071227, and 090510 from ground-based observations (Berger et al. 2009; Rau et al. 2009). In the case of GRBs 070724 and 071227 the optical afterglows coincide with the disks of edge-on spiral galaxies (Figure 1; Berger et al. 2009; D'Avanzo et al. 2009). The offsets of the three bursts are 4.8, 14.8, and 5.5 kpc, respectively.

There are 7 additional events with optical afterglow identifications. Of these bursts, two (070707 and 070714b) coincide with galaxies (Piranomonte et al. 2008; Graham et al. 2009), but their offsets have not been measured by the respective authors. Based on the claimed coincidence we conservatively estimate an offset of $\lesssim 0.5''$, corresponding[2] to $\lesssim 4$ kpc. Two additional bursts (070809 and 080503) do not have coincident host galaxies to deep limits, but the nearest galaxies are located about 6.5 and 20 kpc from the afterglow positions, respectively[3] (Perley et al. 2008, 2009). For the final three bursts (080905, 090305, and 090426) no deep host galaxy searches exist in the literature.

In addition to the bursts with sub-arcsecond positions, several hosts have been identified within XRT error circles in follow-up observations (GRBs 060801, 061210, 061217, 070429b, 070729, and 080123; Berger et al. 2007b; Berger 2009). Since the putative hosts are located within the error circles, in all of these cases the offsets are consistent with zero or may be as large as ~ 30 kpc (e.g., Berger et al. 2007b). For example, the offsets for GRBs 060801, 061210, and 070429b are 19 ± 16 kpc, 11 ± 10 kpc, and 40 ± 48 kpc. We use 30 kpc as a typical upper limit on the offset for these 6 events. We note that no follow-up observations are available in the literature for most short GRBs with X-ray positions from 2008-2009. Finally, about

[2]GRB 070714b is located at $z=0.923$, while the redshift of GRB 070707 is not known. Based on the faintness of the host, $R\approx 27.3$ mag, we assume $z=1$ to calculate the physical offset.

[3]GRB 070809 is located 19.6 kpc from a galaxy at $z=0.219$, and about $2.3''$ from a much fainter galaxy, which at $z\gtrsim 1$ corresponds to 18.4 kpc. No host is detected at the position of GRB 080503 in deep *HST* observations, but a faint galaxy is located about $0.8''$ away, which at $z\gtrsim 1$ corresponds to 6.5 kpc.

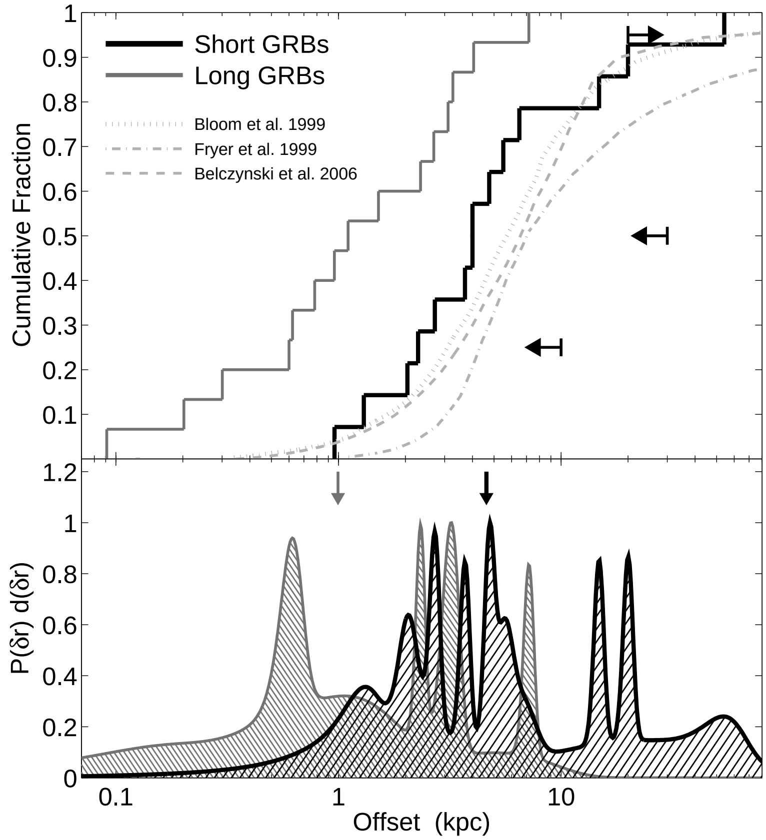

Figure 9: Projected physical offsets for short GRBs (black) and long GRBs (gray; Bloom et al. 2002). The top panel shows a cumulative distribution, while the bottom panel shows the differential distribution taking into account the non-Gaussian errors on the offsets. The arrows in the bottom panel mark the median value for each distribution. The median value for short GRBs, ≈ 5 kpc, is about a factor of 5 times larger than for long GRBs. The arrows in the top panel exhibit the most robust constraints on the offset distribution, taking into account the fraction of short GRBs with only γ-ray positions, as well as short GRBs for which hosts have been identified within XRT error circles (thereby providing a typical range of $\sim 0-30$ kpc). Also shown in the top panel are predicted offset distributions for NS-NS binary mergers in Milky Way type galaxies based on population synthesis models. We find good agreement between the observed distribution and models, as well as between the robust constraints and models. From Fong et al. (2009).

$1/4-1/3$ of all short GRBs discovered to date have only been detected in γ-rays with positional accuracies of a few arcminutes, thereby precluding a unique host galaxy association and an offset measurement.

The cumulative distribution of projected physical offsets for the GRBs with *HST* observations from our work (Fong et al. 2009), supplemented by the bursts with offsets or limits based on optical afterglow positions (070707, 070714b, 070724, 070809, 071227, 080503, and 090510) is shown in Figure 9. Also shown is the differential probability distribution, $P(\delta r)d(\delta r)$, taking into account the non-Gaussian errors on the radial offsets (see discussion in Appendix B of Bloom et al. 2002). We find that the median for this sample is about 5 kpc.

As evident from the discussion above, this is not a complete offset distribution; roughly an equal number of short GRBs have only limits or undetermined offsets due to their detection in

just the X-rays or γ-rays[4]. Taking these events into account, our most robust inferences about the offset distribution of short GRBs are as follows:

- At least 25% of all short GRBs have projected physical offsets of $\lesssim 10$ kpc.
- At least 5% of all short GRBs have projected physical offsets of $\gtrsim 20$ kpc.
- At least 50% of all short GRBs have projected physical offsets of $\lesssim 30$ kpc; this value includes the upper limits for the hosts identified within XRT error circles.

These robust constraints are shown in Figure 9.

We compare the observed distribution and the robust constraints outlined above with predicted distributions for NS-NS binaries in Milky Way type galaxies (Bloom et al. 1999; Fryer et al. 1999; Belczynski et al. 2006), appropriate for the observed luminosities of short GRB host galaxies (Berger 2009). We find good agreement between the observed distribution and those predicted by Bloom et al. (1999) and Belczynski et al. (2006). The offset distribution of Fryer et al. (1999), with a median of about 7 kpc, predicts larger offsets and therefore provides a poorer fit to the observed distribution, which has a median of about 5 kpc. However, all three predicted distributions accommodate the offset constraints. In particular, they predict about $60 - 75\%$ of the offsets to be $\lesssim 10$ kpc, about $80 - 90\%$ to be $\lesssim 30$ kpc, and about $10 - 25\%$ of the offsets to be $\gtrsim 20$ kpc. Thus, the projected physical offsets of short GRBs are consistent with population synthesis predictions for NS-NS binaries. However, the observations are also consistent with partial contribution from other progenitor systems with no expected progenitor kicks, such as WD-WD binaries.

We compare our observed short GRB offsets with those of long GRBs from the sample of Bloom et al. (2002) in Figure 9. The offset distribution of long GRBs has been used to argue for a massive star progenitor population, and against NS-NS binaries (Bloom et al. 2002). The offset distribution for short GRBs is clearly shifted to larger physical scales. In particular, the median offset for the long GRBs is 1.1 kpc, about a factor of 5 times smaller than the median value for short GRBs. Similarly, no long GRB offsets are larger than about 7 kpc, whereas at least some short GRBs appear to have offsets in excess of 15 kpc.

In the context of NS-NS binary progenitors, the close similarity in the normalized offset distributions can be interpreted to mean that most systems likely remain bound to their hosts (rather than ejected into the intergalactic medium), and/or have a relatively short delay time. These conclusions are tentative due to the small number of events with host-normalized offsets, but they can be further tested with future *HST* observations.

4.3 Light Distribution Analysis

In addition to the offset analysis in the previous section, we study the local environments of short GRBs using a comparison of their local brightness to the host light distribution. This approach is advantageous because it is independent of galaxy morphology, and does not suffer from ambiguity in the definition of the host center (see Fruchter et al. 2006). We note that for the overall regular morphology of short GRB hosts the definition of the host center is generally robust, unlike in the case of long GRBs (Fruchter et al. 2006; Wainwright et al. 2007). On the other hand, this approach has the downside that it requires precise pixel-scale positional accuracy. In our sample, this is the case for only 6 short bursts.

[4]We do not consider the bursts that lack host searches since there is no a priori reason that these events (mainly from 2008-2009) should have a different offset distribution compared to the existing sample from 2005-2007.

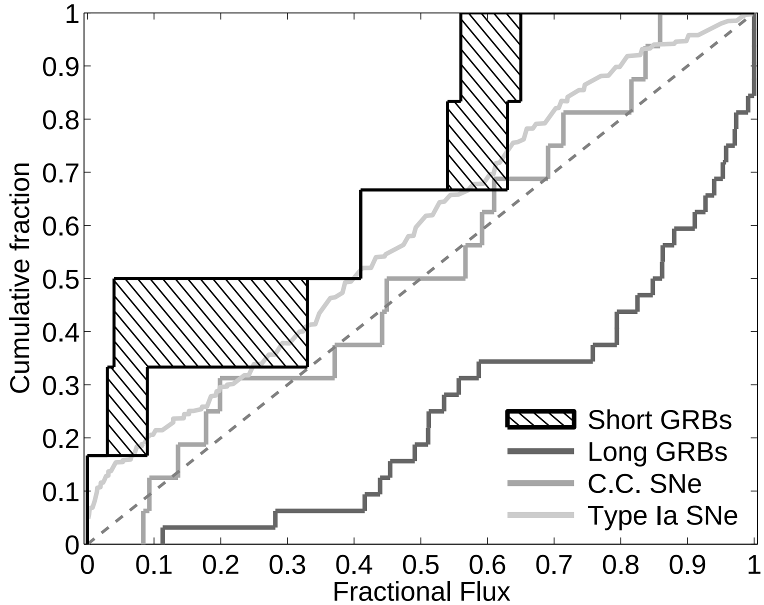

Figure 10: Cumulative distribution of fractional flux at the location of short GRBs relative to their host light. For each burst we measure the fraction of host light in pixels fainter than the GRB pixel location. The shaded area is defined by the results for the two available filters for each short GRB. Also shown are data for long GRBs (dark gray line) and for core-collapse and Type Ia SNe (light gray lines) from Fruchter et al. (2006) and Kelly et al. (2008). The dashed line marks the expected distribution for objects which track their host light distribution. Short GRBs appear to under-represent their host light, while long GRBs tend to be concentrated in the brightest regions of their hosts (Fruchter et al. 2006). From Fong et al. (2009).

The fraction of host light in pixels fainter than the afterglow pixel brightness for each host/filter combination is given in Fong et al. (2009). The cumulative light distribution histogram is shown in Figure 10. The shaded histogram represents the range defined by the dual filters for 5 of the 6 bursts. We find that the upper bound of the distribution is defined by the blue filters, indicating that short GRBs trace the rest-frame optical light of their hosts better than the rest-frame ultraviolet. This indicates that short GRB progenitors are likely to be associated with a relatively old stellar population, rather than a young and UV bright population.

The overall distribution has a median value of $\approx 0.1 - 0.4$ (red); namely, only in about one-quarter of the cases, 50% of the host light is in pixels fainter than at the GRB location. Thus, the overall distribution of short GRB locations under-represents the host galaxies' light distribution. This is also true in comparison to the distribution for core-collapse SNe, which appear to track their host light (Fruchter et al. 2006), and even Type Ia SNe, which have a median of about 0.4 (Kelly et al. 2008). Thus, the progenitors of short GRBs appear to be more diffusely distributed than Type Ia SN progenitors.

An extensive analysis of the brightness distribution at the location of long GRBs has been carried out by Fruchter et al. (2006). These authors find that long GRBs are more concentrated on the brightest regions of their hosts than expected from the light distribution of each host. In particular, they conclude that the probability distribution of GRB positions is roughly proportional to the surface brightness squared. As can be seen from Figure 10, short GRBs have a significantly more diffuse distribution relative to the host light than long GRBs. In particular,

for the latter, the median light fraction is about 0.85 compared to about 0.25 ± 0.15 for the short GRBs.

4.4 Implications for the Progenitors

Our extensive analysis of short GRB host galaxy morphologies and the burst local environments has important implications for the progenitor population. We address in particular the popular NS-NS merger model, as well as delayed magnetar formation via WD-WD mergers or WD accretion-induced collapse (Metzger et al. 2008).

Morphology: From the morphological analysis we find continued evidence that the bulk of short GRB host galaxies ($\sim 3/4$) are late-type galaxies, in agreement with results from spectroscopic observations (Berger 2009). Moreover, as demonstrated by the systematic differences in luminosity, star formation rates, and metallicities between the star forming hosts of long and short GRBs (Berger 2009), we find that short GRB hosts are systematically larger than long GRB hosts. These results indicate that the progenitors of the two GRB classes select different environments. The higher luminosities, larger sizes, and lower specific star formation rates of short GRB hosts suggest that their rate of occurrence is tied to galactic mass rather than to star formation activity. This result is in broad agreement with old progenitor populations such as NS-NS, NS-BH, or WD-WD binaries, but it indicates that the bulk of short GRB progenitors are not young magnetars. This conclusion is also supported by the dearth of galaxy merger signatures, which point to delays of $\gtrsim 10^9$ yr relative to any merger-triggered star formation episodes.

Offsets: The differential offsets measured from the *HST* observations provide the most precise values to date for short GRBs, with a total uncertainty of only $\sim 10 - 60$ mas, corresponding to $\sim 30 - 500$ pc. We find that none of the offsets are smaller than ~ 1 kpc, while this is the median offset for long GRBs. On the other hand, a substantial fraction of the *measured* offsets are only a few kpc. The median offset for the *HST* observations supplemented by ground-based data is about 5 kpc (Figure 9), about 5 times larger than for long GRBs.

As discussed above, the observed offset distribution is incomplete. About $1/4 - 1/3$ of all short GRBs have only γ-ray positions ($\sim 1 - 3'$), and a similar fraction have only XRT positions, which generally lead to a range of offsets of $\sim 0 - 30$ kpc. Taking these limitations into account we find that the most robust constraints on the offset distribution are that $\gtrsim 25\%$ of all short GRBs have offsets of $\lesssim 10$ kpc, and that $\gtrsim 5\%$ have offsets of $\gtrsim 20$ kpc. Both the observed offset distribution and these constraints are in good agreement with predictions for the offset distribution of NS-NS binaries in Milky Way type galaxies (Bloom et al. 1999; Fryer et al. 1999; Belczynski et al. 2006). However, at the present they cannot rule out at least a partial contribution from other progenitor systems such as delayed magnetar formation and even young magnetar flare. The apparent existence of large offsets in the sample suggests that these latter models are not likely to account for *all* short GRBs.

In the context of implications for the progenitor population, a recent study of short GRB physical offsets by Troja et al. (2008) led these authors to claim that short GRBs with extended X-ray emission have systematically smaller offsets, possibly due to a systematic difference in the progenitors. Our *HST* sample includes three short GRBs with strong extended emission (050709, 050724, and 061006), and one GRB (060121) with possible extended emission (4.5σ significance; Donaghy et al. 2006). The physical offsets of these bursts are about 3.7, 2.7, 1.3, and 1 kpc, respectively, leading to a mean offset of about 2.2 kpc. The physical offsets of the bursts without extended emission, but with precise afterglow positions (051221, 060313, and 061201) are 2.0,

2.3, and 14.2 or 32.5 kpc, respectively. The two events with no extended emission and with XRT positions (050509b and 051210) have offsets of about 54 ± 12 and 28 ± 23 kpc, respectively. Including the ground-based sample with optical afterglow positions, we find that the bursts with apparent extended emission (070714b, 071227, 080513, and 090510; Barbier et al. 2007; Sakamoto et al. 2007; Ukwatta et al. 2009; Perley et al. 2009) have offsets of $\lesssim 4$, 14.8, ~ 20, and ~ 5.5 kpc, while the bursts without extended emission (070724 and 070809) have offsets of 4.8 and ~ 6.5 kpc. Thus, based on the sample of events with sub-arcsecond positions we find that 6/8 bursts with extended emission have offsets of $\lesssim 5$ kpc and 2/8 have likely offsets of $\sim 15 - 20$ kpc. In the sample without extended emission we find that 4/5 have offsets of $\lesssim 6$ kpc and 1/5 has a likely offset of $\sim 14 - 32$ kpc. Thus, we conclude that there is no significant difference in the two offset distributions.

The inclusion of events with only XRT positions does not change this conclusion. In particular, of the subset with no extended emission only GRB 050509b is likely to have a significant offset, while GRBs 051210, 060801, and 070429b have offsets (28 ± 23, 19 ± 16, and 40 ± 48 kpc, respectively) that are consistent with zero. Similarly, GRB 061210 with extended emission has an offset of 11 ± 10 kpc. An examination of the sample of Troja et al. (2008) reveals that their claim that short GRBs without extended emission have systematically larger offsets rests on four events in particular: GRBs 050509b, 060502b, 061217, and 061201. As noted above, GRBs 050509b and 061201 indeed appear to have substantial offsets, but so do GRBs 071227 and 080503 with extended emission and offsets of about $15 - 20$ kpc. Next, the large offset for GRB 060502b relies on its claimed association with an elliptical galaxy 70 ± 16 kpc from the XRT position (Bloom et al. 2007). However, the XRT error circle contains additional galaxies with negligible offsets (Berger et al. 2007b). Finally, we note that the offset for GRB 061217 is unreliable due to a substantial discrepancy of about $33''$ in the XRT positions from Butler (2007) and Evans et al. (2009). A continued investigation of the difference between short GRBs with and without extended emission will greatly benefit from the use of host-normalized offsets.

Light Distribution: In addition to projected offsets relative to the host center, we find that the locations of the short GRBs with *HST* imaging and sub-arcsecond positions are more diffusely distributed relative to their host light than long GRBs. In particular, we find that short GRB positions under-represent their host light, even in comparison to core-collapse and Type Ia SNe. This result is likely an upper limit on the brightness of short GRB locations since only the subset of events with optical afterglow positions can be studied with this approach. Thus, short GRBs arise from a population of events with a more diffuse distribution than massive stars and Type Ia SN progenitors. This result also indicates that the bulk of the progenitors of long and short GRBs cannot both be magnetars.

There are currently 10 known short GRBs with optical afterglows for which *HST* observations will enable a similar analysis. This is twice the number of the current sample, and we can therefore make significant progress in understanding the relation of short GRB environments to the overall distribution of light in their host galaxies with future observations.

5 Conclusions

While the sample of short GRBs with afterglow positions is still significantly smaller than the sample of long GRBs, we have began to make significant progress in understanding their galactic and sub-galactic environments. The results of spectroscopic and high resolution imaging observations point to an association of short GRBs with faint regions of normal star forming and

elliptical galaxies. In nearly every respect (star formation rates, metallicities, sizes, offsets, light distribution) the environments of short GRBs are distinct from those of long GRBs, indicating that they are not related to a young progenitor population. The bulk of the evidence indicates an association with an old stellar population, and the observations are fully consistent with NS-NS binary mergers. However, a partial contribution from prompt or delayed magnetar formation cannot be ruled out at the present. We expect that studies of the ever-growing sample of short GRBs similar to the ones presented in this review will eventually constrain the contributions of various progenitors models.

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